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Boundary-Layer Transition Measurements in Hypervelocity Flows in a Shock Tunnel

David J. Mee*
University of Queensland, Brisbane, Queensland 4072, Australia

Experiments to investigate the transition process in hypervelocity boundary layers were performed in the T4 free-piston shock tunnel. An array of thin-film heat-transfer gauges was used to detect the location and extent of the transitional region on a 1500 mm long × 120 mm wide flat plate, which formed one of the walls of a duct. The experiments were performed in a Mach 6 flow of air with 6- and 12-MJ/kg nozzle-supply enthalpies at unit Reynolds numbers ranging from 1.6×10^6 to 4.9×10^6 m^{-1}. The results show that the characteristics typical of transition taking place through the initiation, growth, and merger of turbulent spots are evident in the heat-transfer signals. A 2-mm-high excrescence located 440 mm from the leading edge was found to be capable of generating a turbulent wedge within an otherwise laminar boundary layer at a unit Reynolds number of 2.6×10^6 m^{-1} at the 6-MJ/kg condition. A tripping strip, located 100 mm from the leading edge and consisting of a line 37 teeth of 2 mm height equally spaced and spanning the test surface, was also found to be capable of advancing the transition location at the same condition and at the higher enthalpy condition.

I. Introduction

THE state of the boundary layers on high-speed flight vehicles, that is, whether they are laminar or turbulent, significantly influences the heat transfer to such vehicles and their drag. Because of its importance, transition in high-speed flows has been the subject of many investigations over the past half-century.

As flight speed increases, not only does the Mach number increase, but the air temperature increases in stagnation regions and in boundary layers. In air, as the temperature increases, vibrational excitation and chemical reaction effects (dissociation and ionization) become increasingly important.[1] Heat-transfer levels in both laminar and turbulent layers also become very high as the difference between the recovery temperature and the surface temperature increases with flight speed. There has been only limited experimental study of transition in the hypervelocity flow regime where chemical activity can influence the processes (for example, see Refs. 2–5). These shock-tunnel studies indicate a change in transition Reynolds number with changes in the total enthalpy of the flow. Adam and Hornung[4] attributed a delay in transition at higher enthalpies to real-gas effects on second-mode acoustic instabilities in the boundary layer. Rasheed et al.[5] showed that transition location could be delayed in the boundary layer on a sharp cone in hypervelocity flows by a passive technique for attenuation of these acoustic disturbances.

A trend of increased difficulty of tripping a boundary layer from laminar to turbulent flow as the Mach number increases has been observed,[6] and forced transition at hypervelocity conditions is also of interest. Isolated roughness effects on the Space Shuttle Orbiter, associated with joints and misalignment of the thermal protection tiles, have been shown to influence boundary-layer transition.[7] The Hyper-X scramjet-powered test vehicle[8] incorporates boundary-layer trips on the forebody. These are designed to trip the boundary layer on the underside of the vehicle from laminar to turbulent flow before it is ingested into the engine. Ingestion of a turbulent rather than a laminar boundary layer into the engine reduces susceptibility to boundary-layer separation within the engine (which can lead to engine unstart) and enhances fuel mixing.[9]

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*Senior Lecturer, Department of Mechanical Engineering; mee@mech.uq.edu.au. Member AIAA.

A developing boundary layer can be in one of four flow states as it grows on a surface; it can be laminar and stable, laminar but unstable, intermittent turbulent, or fully turbulent. A boundary layer is usually identified as being transitional when it is in the intermittent turbulent regime. This flow regime is characterized by regions of turbulent flow that can vary in space and time. The focus of this study is the intermittent turbulent region in hypervelocity flows. However, the precursor to this—the growth of disturbances in the unstable laminar boundary layer—can influence the transition process and thus the flow in the intermittent turbulent region.

There have been a number of studies of the flow in the unstable laminar layer in hypersonic flows (for example, see Refs. 10–12) stemming from the work of Mack,[13] where second-mode instabilities were identified. For thin boundary layers in hypervelocity flows, the frequencies of the second mode disturbances can be very high. For example, Germain and Hornung[3] report a second-mode frequency of 1.5 MHz for their transition measurements on a 5-deg cone in the T5 free-piston shock tunnel at Mach 6, 11 MJ/kg stagnation enthalpy, and 5.4×10^6 m^{-1} unit Reynolds number.

Turbulent spots have been studied extensively in incompressible flows.[14] However, less work has been done in the compressible flow regime. Although a number of studies using flow visualization or surface instrumentation have indicated that turbulent spots are present in compressible transitional flows (for example, see Refs. 15 and 16), less work has been done to quantify the dynamics of the spots.[17,18]

Fischer[19] collated published and unpublished data for flow Mach numbers up to 14 and looked at the spreading rates of spots and turbulent wedges. He identified a rapid reduction in lateral spreading angles as the Mach number increased (see Fig. 1). More recently, a theoretical analysis by Doorly and Smith[20] predicts that spreading angles also decrease with Mach number. If the predictions of Doorly and Smith are compared with Fischer's data, quite good agreement is observed (see Fig. 1).

The transition studies that have been undertaken in hypervelocity flows (for example, see Refs. 2–4). have focused more on the mean quantities in the boundary layers rather than on the unsteady processes occurring through transition. The investigation of Rasheed et al.[5] shows that a dense array of small, blind holes in the surface can delay transition on a cone in Mach 6 hypervelocity flows in a shock tunnel. The purpose of the holes is to attenuate the acoustic second-mode disturbances, and the fact that transition can be delayed using this technique suggests that this mode is dominant at such conditions.

Irrespective of the mechanism by which the instabilities arise, it is apparent that the final breakdown of the laminar layer occurs

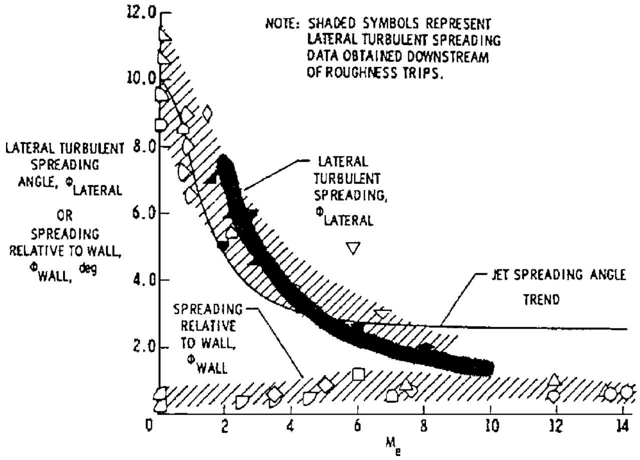


Fig. 1 Spreading angles of Fischer[19] with prediction of Doorly and Smith[20] (thick line).

via turbulent spot formation. One significant feature of the dynamics of turbulent spots is that the length of the transition region is determined by the merging of spots. This merging will depend on the spot formation rate, the distribution of spot initiation sites, and the growth of the spots as they convect downstream. The speed of the head and the tail of the spots and the spreading angle of the spots will affect their growth rate and subsequently their merger with other spots and thus the transition length. Thus knowledge of how turbulent spots are formed and grow is important for determining how surface quantities, such as heat transfer and skin friction, vary in the transitional boundary layer. Kimmel[21] postulates the importance of turbulent spot spreading rates in determining how transition length varies with pressure gradients in hypersonic flows and notes that detailed measurements of the transition process are required.

Mee and Goyne[18] identified turbulent spot activity in a flat-plate boundary layer in the T4 shock tunnel using a line of heat-transfer gauges down the centerline of one of the walls of a 1.5-m-long duct. The results demonstrated that thin-film gauges are well suited for studying transient heat transfer in a transitional hypervelocity boundary layer and were shown to be capable of detecting and quantifying turbulent spot activity. In a Mach 6 flow turbulent spots were clearly identified.

The aims of the present study are to investigate the details of the flow in the intermittent turbulent region in hypervelocity boundary layers undergoing both forced and unforced transition. Section II describes the experiments performed in the T4 shock tunnel, including experiments with a clean flat-plate configuration as well as tests with isolated and multiple transition promoters. Section III presents the main results obtained during the tests.

II. Experiments

The experiments were performed in the T4 free-piston shock tunnel at the University of Queensland.[22] This facility is capable of producing flows with nozzle-supply enthalpies up to 15 MJ/kg with flow durations ranging from 1 to 5 ms. A Mach 6, axisymmetric, contoured nozzle was used. The basic model arrangement was the same as that used in Mee and Goyne[18]; however, a new test surface with more densely packed instrumentation was installed. The test surface was a flat plate 1500 mm long. The plate formed one of the inner walls of a duct that captured the flow from an opening 120 mm wide and 60 mm high. Adjustable divergence on the three noninstrumented walls enabled pressure gradients on the test surface to be varied over a small range. Divergence of 0.5 deg on these surfaces was used in the present tests to produce a small, favorable pressure gradient down the duct. Flush-mounted thin-film heat-transfer gauges (TFGs) were used to measure surface heat-transfer rates. These gauges, manufactured in-house, consist of a nickel film, 1 mm long × 0.3 mm wide × 0.1 μm thick, deposited onto a fused quartz cylinder of 2.1-mm diam. For these gauges and the associated instrumentation it is estimated that the 10–90% rise time in response to a step change in heat transfer is 2 μs. This is

Table 1 Nominal test conditions

Condition	Low H_s Low Re	Low H_s Mid Re	Low H_s High Re	High H_s Low Re
Nozzle-supply enthalpy, MJ/kg	5.3	6.2	6.8	12.4
Mach number	6.3	6.2	6.1	5.5
Flow speed, m/s	2980	3210	3370	4330
Static pressure, kPa	2.8	5.4	12.1	9.4
Static temperature, K	570	690	800	1560
Static density, kg/m^3	0.017	0.027	0.053	0.020
Ratio of specific heats	1.38	1.37	1.36	1.33
Unit Reynolds number, m^{-1}	1.7×10^6	2.6×10^6	4.9×10^6	1.6×10^6

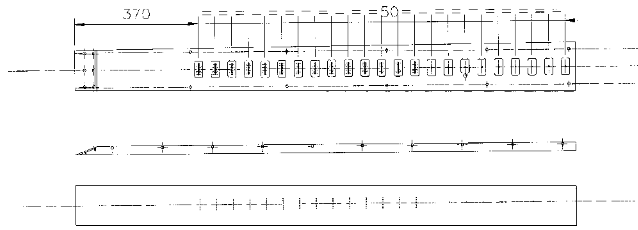


Fig. 2 Test plate showing locations available for heat-transfer gauges (dimensions in millimeters).

based on the properties of the film and substrate and the analysis presented in Sec. 2.c of Schultz and Jones.[23] The thin-film gauge signals were multiplexed such that the signal from each transducer was sampled at 4-μs intervals. The signals from the thin-film gauges were processed digitally to determine heat-transfer levels using the techniques described in Schultz and Jones.[23]

Locations on the test surface that were available for installation of thin-film gauges are shown in Fig. 2. At 14 streamwise locations provision was made for seven gauges to be placed with a spanwise spacing of 5 mm. A further nine locations on the centerline were provided downstream of the array. This arrangement enables not only the streamwise but also the spanwise propagation of disturbances to be studied. The available instrumentation enabled up to 50 TFG signals to be recorded in a single test.

Experiments were performed in a test gas of air at nozzle-supply enthalpies of 6 and 12 MJ/kg. At the lower enthalpy condition the unit Reynolds number (based on freestream conditions) was varied from 1.7×10^6 m^{-1} to 4.9×10^6 m^{-1}. At the high enthalpy condition the unit Reynolds number was 1.6×10^6 m^{-1}. The nominal test conditions at entry to the duct are summarized in Table 1. Experiments with the same test geometry[24] indicate that there are small favorable mean pressure gradients down the test surface. At the low enthalpy condition the mean pressure drops approximately 10% over the measurement region, and at the high enthalpy condition the pressure drops approximately 20%.

Tests were made with a smooth test surface and with isolated and multiple roughness elements to investigate whether transition could be tripped. The rounded isolated roughness element was 5 mm in diameter and 2 mm high. This was located 2.5 mm off the centerline of the plate, 440 mm from the leading edge. The multiple roughness element case used a row of 37 approximately triangular teeth that were 2 mm high and were equally spaced 3 mm apart. The row of teeth spanned the test surface 100 mm from the leading edge.

III. Results and Discussion

A nozzle supply pressure signal, typical of the present experiments, is shown in Fig. 3. This pressure is measured on the sidewall, 100 mm from the downstream end of the shock tube. This result is for the low enthalpy, mid-Reynolds-number condition. It can be seen that, after about 0.7 ms, the pressure reaches a steady level and remains steady for another 2 ms. Until this time measurements indicate that the test gas is free from contamination by the driver gas.[25]

Two heat-transfer signals for the same test are shown in Fig. 4. These signals are from gauges in the laminar region, 370 mm from the leading edge of the plate, and in the turbulent region, 1370 mm from the leading edge. At the upstream gauge location the boundary

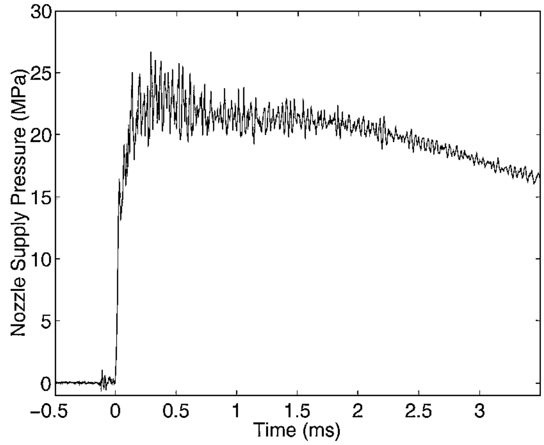


Fig. 3 Nozzle-supply pressure for shot 6910, low H_s, mid Re.

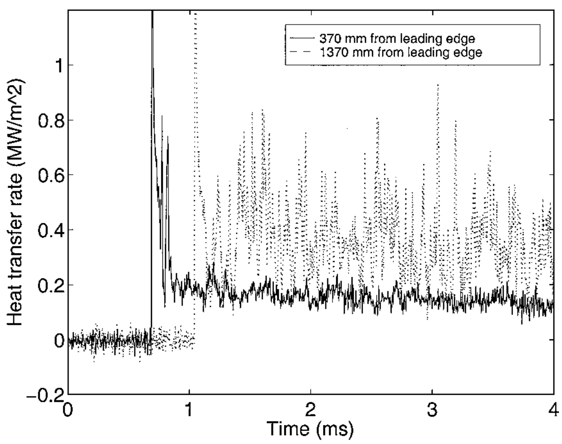


Fig. 4 Heat-transfer signals for shot 6910, low H_s, mid Re.

layer is laminar, and at the downstream gauge it is turbulent. Both the heat-transfer level and the magnitude of the fluctuating heat transfer are higher in the turbulent region. The results also show that the flow arrives at the gauge closer to the leading edge about 300 μs before it arrives at the downstream gauge. Time zero is set to be the time when the shock reflects in the nozzle-supply region (see Fig. 3). About 1.5 ms after flow arrival, the flow becomes established, and heat-transfer levels reach approximately a constant level, which is maintained for another 1.0 ms. After 1.5 ms the flow will have travelled approximately three times the model length. Beyond 2.5 ms after flow arrival, the heat-transfer level then drops as the nozzle-supply pressure decreases, and the test gas becomes contaminated. In subsequent analysis of the data, mean heat-transfer levels are taken as an average during the period of steady flow after the flow establishment time.

Figure 4 also indicates the signal-to-noise ratio for the heat-transfer traces. Noise on the temperature signals indicated by the thin-film gauges is amplified when signals are processed to infer the heat-transfer rates. The noise level as a result of this can be estimated from the signals from the gauges before the arrival of flow. The standard deviation of the heat-transfer traces for the gauge 370 mm from the leading edge in the first 0.5 ms of the trace in Fig. 4 is 20 kW/m^2. The standard deviation for this gauge during the test period is 30 kW/m^2. Thus, some of the high-frequency fluctuation in the signal from this gauge, which is in the laminar region of the boundary, can be attributed to noise in the instrumentation. For the gauge in the turbulent region, the noise level rises from a standard deviation of 25 kW/m^2 before the flow to 140 kW/m^2 during the test period.

A. Smooth Plate

Heat-transfer rates measured at each of the test conditions for the "clean" configuration (no transition trips) are shown in Fig. 5. Data from all gauges for which signals were recorded are included. The heat-transfer signals were averaged during the period of steady flow. An averaging time of 1.0 ms was used for the low enthalpy conditions, and 700 μs was used at the high enthalpy condition. Where more than one TFG was located at a given distance from the leading edge of the plate, results were averaged. Thus some points represent the average from up to six gauges, and others are from a single gauge. Shown also are theoretical laminar and turbulent heat-transfer levels. The laminar level is calculated using a reference enthalpy method,[26] and the turbulent levels are calculated using the method of van Driest II.[27] The origin for both the laminar and turbulent prediction is taken as the leading edge of the plate.

The uncertainty in Stanton number for these tests is estimated to be $\pm 18\%$ (Ref. 24). When results from a number of gauges are averaged at a particular distance from the leading edge, the uncertainty in the mean will be lower. Some repeat tests were performed, and results are shown in Figs. 5b and 5c. As can be seen, the results repeat well in both Stanton-number level and in transition location.

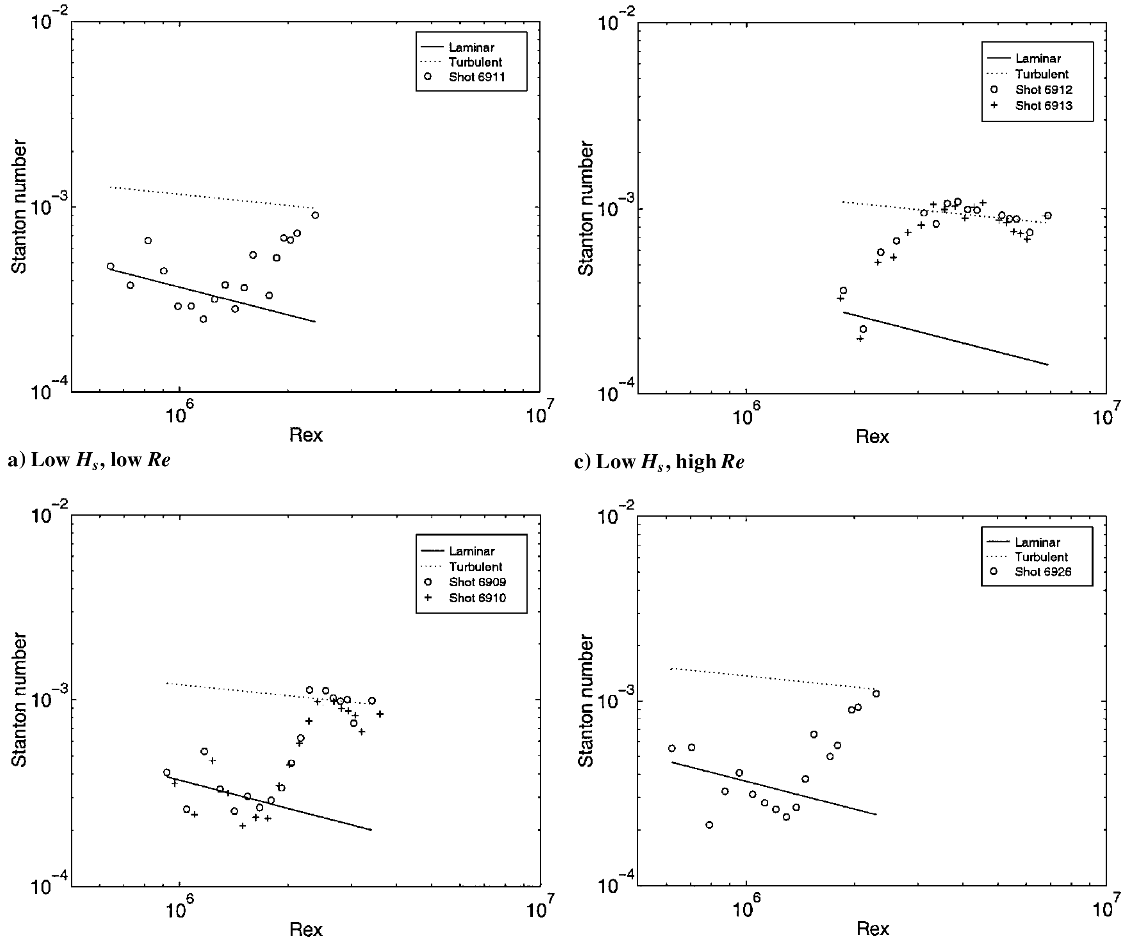
The forward movement of transition location as the Reynolds number is increased was observed in the results from the low enthalpy conditions with the location where the heat-transfer level rises above the laminar level moving closer to the leading edge as the Reynolds number increases. At low enthalpy the transition Reynolds numbers vary from 1.6×10^6 to 1.8×10^6 to 2.2×10^6 for the low-, mid-, and high-Reynolds-number conditions, respectively. The location of transition onset is taken to be where the mean heat-transfer level first rises above the laminar level. Thus the unit Reynolds-number effect on transition Reynolds number, which has been observed in many previous studies,[28] is also apparent in the current results. At the high enthalpy condition the transition Reynolds number is 1.5×10^6, close to the value obtained at the same unit Reynolds number at the lower enthalpy. He and Morgan,[2] in tests on an open flat plate, found similarly that the transition Reynolds number correlated well with unit Reynolds for a range of stagnation enthalpies.

Of interest here is the flow in the intermittent turbulent region of the boundary layer. Previous experiments in the T4 shock tunnel indicate that transition takes place through the initiation, merger, and growth of turbulent spots.[18] The fast responses of TFGs make them suitable for identifying the fluctuations in heat transfer to the surface that occurs when turbulent patches pass over the gauge.

An example of the measured heat-transfer time histories from 50 gauges is shown in Fig. 6. These traces are from shot 6910 at the low enthalpy, mid-Reynolds-number condition. Each trace shows the local laminar and turbulent heat-transfer levels and is for 1-ms duration during the steady flow test time. The location of the plot corresponds to the location of the gauge on the test plate (see the caption for the figure). Some of the gauges failed during the tests so that a complete array of signals was not obtained.

The boundary layer is initially laminar but starts to undergo transition at about the sixth row of gauges. The passage of a turbulent spot over a gauge can be identified by a sharp increase in the heat-transfer rate toward the turbulent level, and the end of the passage of the spot over the gauges sees the rate return to the laminar level. At the seventh row of gauges, it can be seen that no turbulent spots pass over some gauges (see signals from gauges marked a and b). Other gauges detect spots at the same time (note the spikes in signals from gauges marked d, e, and f at about 50 μs into the trace). This is interpreted as the same spot being of large enough spanwise extent to simultaneously cover more than one gauge. The signal from the gauge marked c indicates a spot at about 800 μs into the trace, which is not detected at either gauges b or d. Thus, it is apparent that spots of different spanwise extent are present at this location.

The streamwise extent of the spots can be identified by the simultaneous appearance of the same spot on gauges at different distances from the leading edge. For example, the spot just identified on the gauge marked c can be seen to be simultaneously over gauges immediately upstream and downstream of it. Because the spots initiate naturally, identifying the streamwise extent of a spot can be difficult because of the formation of new spots. However in the case of the spot just identified, it is possible to trace its streamwise and spanwise propagation to determine the growth angle of the spot. Here it is estimated to be 3.5 ± 0.5 deg. This is in good agreement with



a) Low H_s, low Re

c) Low H_s, high Re

b) Low H_s, mid Re

d) High H_s, low Re

Fig. 5 Mean heat-transfer levels measured on test surface.

the data from lower enthalpy flows presented in Fig. 1, indicating that the spreading angles of spots in the present flows are primarily dependent on the freestream Mach number.

Tracking spots as they convect down the test surface allows the speeds of the leading and trailing edges of the spots to be estimated. For the present conditions the speed of the leading edge of the spots is estimated to be $90 \pm 10\%$ of the freestream speed, and the trailing edges are estimated to convect with a speed of $50 \pm 10\%$ of the freestream speed. These convection speeds agree, to within experimental uncertainty, with those reported for artificially generated spots in incompressible flows[29] and for naturally occurring spots in flows up to Mach 1.9 (Ref. 30). The values are a little lower than those reported by Zanchetta and Hillier,[17] for experiments measuring naturally occurring spots on blunt cones in a Mach 9 gun-tunnel flow. They measured convection speeds of the leading and trailing edges of 98 and 68% of the freestream speed, respectively.

The initiation of new turbulent spots and their growth can be identified in the traces in Fig. 6. More spots are initiated as the Reynolds number increases (greater distances from the leading edge). Finally, it can be seen that the boundary layer reaches a fully turbulent state within the measurement region. The point at which spots are initiated corresponds with the location where the mean heat-transfer rate starts to rise above the laminar level (see Fig. 5b). The end of the appearance of spots corresponds to the location where a maximum mean heat-transfer level is measured.

In summary, the results for the smooth plate show that the flow in the intermittent transitional boundary layer in the current hypervelocity flows is qualitatively similar to that observed in transitional boundary layers in lower enthalpy flows. At the present conditions the results show that turbulent spots grow with a lower semi-angle than at low Mach numbers, in line with the data of Ref. 19 and that spot convection speeds are a similar fraction of the mainstream speed to those observed in lower speed flows. In lower speed flows the Reynolds number based on transition length has been correlated with the Reynolds number based on momentum thickness at the end of transition.[31] The length of transition will be set by the growth and merger of spots. Because the angle at which spots grow is smaller for these higher-Mach-number flows, a greater length would be required for the lateral merging of two spots for a high-Mach-number flow compared with a lower-Mach-number case. Thus a longer transition length might be expected at higher Mach numbers. The current results indicate that transition length Reynolds numbers are in reasonable agreement with the low-speed correlation presented in Ref. 31, and one could therefore postulate that spot initiation rates must be higher in the present flow than for lower speed flows.

B. Plate with Excrescences

Some tests with this model were also performed at Mach 6 with isolated and multiple roughness elements located on the test surface in the laminar region of the boundary layer (an isolated rounded roughness element and a multiple-toothed strip; see Sec. II).

At the location of the tripping strip (100 mm from the leading edge of the plate), the laminar boundary layer has a calculated thickness δ approximately equal to the height of the roughness elements h; δ is calculated to vary from 1.6 to 2.1 mm over the three test conditions, and h is 2 mm. Figure 7 shows the mean heat-transfer levels for the clean and multiple roughness element cases. It can be seen that a multiple roughness trip, with excrescence heights similar to the boundary-layer thickness, is successful in promoting earlier transition for all three test conditions. The roughness Reynolds number Re_k was in excess of 3200 for all cases. $Re_k = u_k k / \nu_k$, where k is the height of the excrescence and u_k and ν_k are, respectively, the flow speed and the kinematic viscosity in the boundary layer at the top of the excrescence.

The effect of the isolated roughness element at the low H_s mid-Reynolds-number condition is shown in Fig. 8. These results can

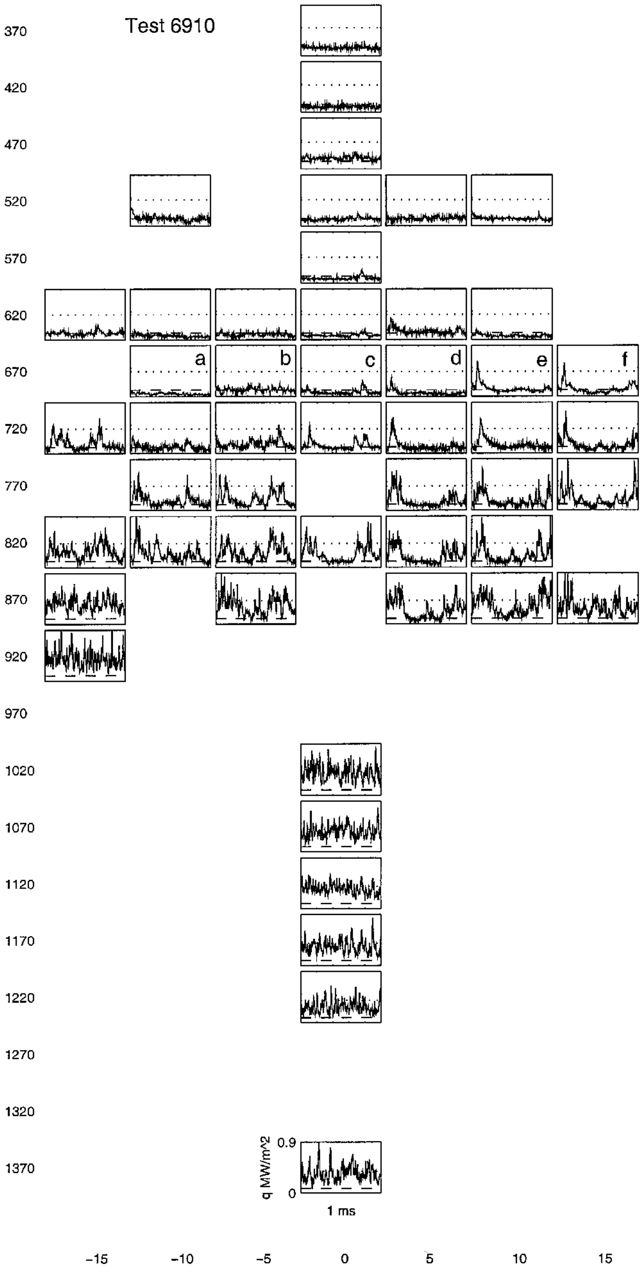
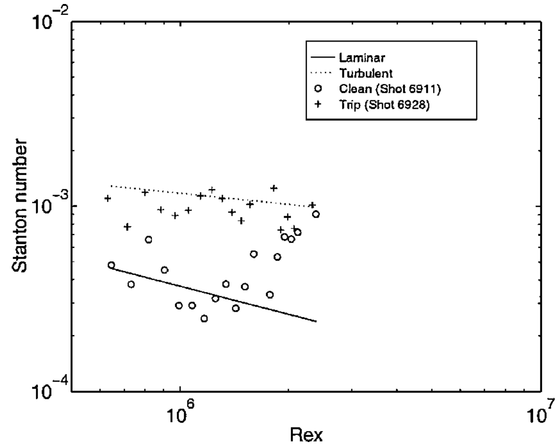
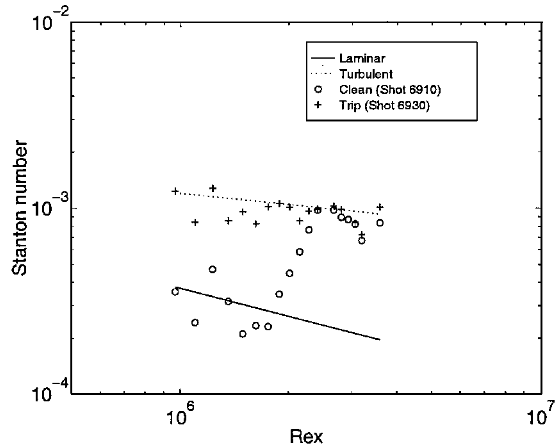


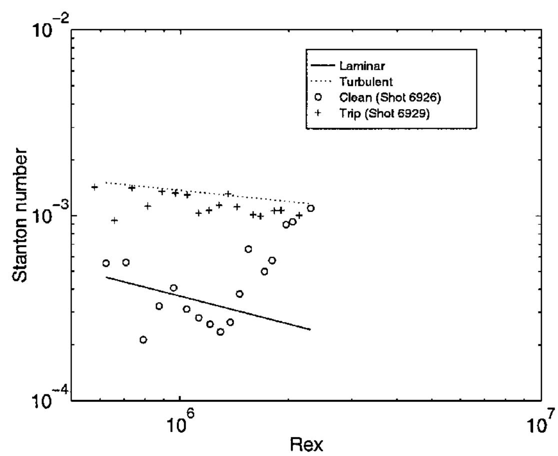
Fig. 6 Heat-transfer traces (——) for the low H_s, mid-Re condition. Each trace is 1-ms duration with a vertical range of 0.9 MW/m^2. Predicted laminar (lower – – –) and turbulent (upper · · · ·) heat-transfer levels are shown for each trace. The top trace is 370 mm from the leading edge, and the bottom is 1370 mm from the leading edge. The streamwise spacing between gauge rows is 50 mm. The spanwise spacing of gauge locations is 5 mm. Trace locations correspond to gauge locations shown in Fig. 2.



a) Low H_s, low Re, h/δ = 0.8



b) Low H_s, mid Re, h/δ = 1.1



c) High H_s, low Re, h/δ = 0.8

Fig. 7 Mean heat-transfer levels for multiple roughness element trip located 100 mm from leading edge.

be compared directly with the results in Fig. 6 for the clean flat-plate case at the same condition. The element was located 2.5 mm to the left of the centerline 440 mm from the leading edge of the plate. Therefore two thin-film gauges were located upstream of the disturbance. The excrescence height is approximately 50% of the calculated laminar boundary-layer thickness at the location of the excrescence and $Re_k = 2100$.

The result shows that the boundary layer is laminar upstream of the excrescence. At the gauge immediately downstream of the disturbance, the heat-transfer level is above the turbulent level predicted for that location. The heat-transfer rate then drops down to the turbulent level at gauges further downstream of the excrescence. The spanwise influence of the disturbance is also apparent, with gauges closest to the centerline of the plate undergoing transition earlier than gauges closer to the edges of the plate. By the seventh row of gauges (670 mm from the leading edge and 230 mm downstream of the excrescence), all but the gauge 15 mm to the right of the centerline (labeled a in Fig. 8) show turbulent heat-transfer levels. The signal from gauge a indicates an intermittent turbulent signal. This suggests a turbulent wedge downstream of the excrescence growing at a semi-angle estimated to be 4 deg at this condition, again in agreement with the results shown in Fig. 1.

There were some differences in the results obtained at the low H_s low-Reynolds-number condition, where the excrescence height was approximately 44% of the boundary layer thickness and $Re_k = 1100$. For the lower-Reynolds-number condition, the heat-transfer rate immediately behind the excrescence also rose above the turbulent level. The enhanced heat-transfer levels behind the disturbances are attributed to vorticity induced by the excrescence. Farther downstream, the heat-transfer levels decreased, and 250 mm downstream

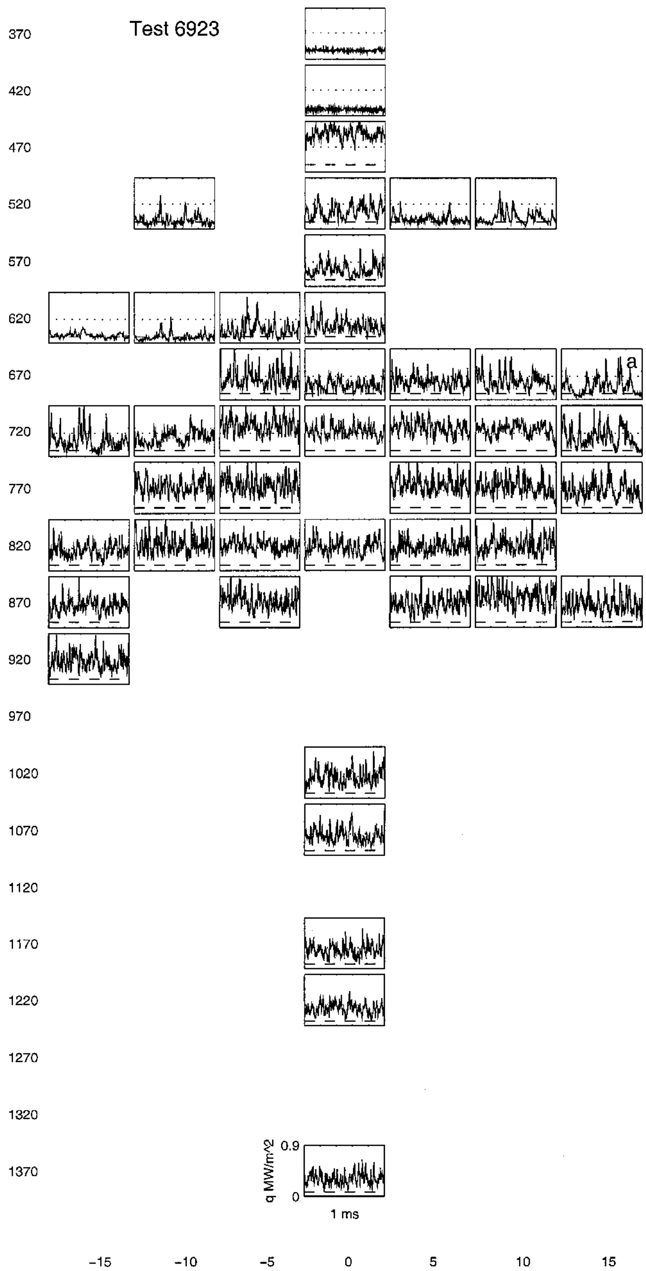


Fig. 8 Effect on heat-transfer rates of an isolated roughness element located 440 mm from leading edge. Low H_s, Mid Re. Each trace is 1-ms duration with a vertical range of 0.9 MW/m^2. (Refer to caption for Fig. 6 for more details.)

of the disturbance the heat transfer had returned to the laminar level. Transition then followed; however, there was evidence of spots appearing earlier and more frequently immediately behind the excrescence. Thus, although the excrescence was not successful in causing transition to occur immediately behind it (that is, it was not an effective trip), the effects of the disturbance continue even though the heat-transfer rate returned to the laminar level. The spanwise extent of the influence of the excrescence for the low-Reynolds-number condition was small. There was no evidence of any effect of the disturbance on the gauges located 5 mm to the right of the centerline of the plate. However, the gauges located 5 mm to the left of the centerline did show some effects of the disturbance.

The roughness Reynolds number Re_k has been found to be useful for determining whether excrescences will trip a boundary layer to turbulence (for example, see Refs. 7, 32, and 33). However, Reda[33] comments that there is no universal value that can be used for determining whether tripping will occur and that the critical value for any combination of flowfield and roughness pattern must be found empirically. He also notes that there can be a significant difference between critical values of Re_k for isolated and distributed three-dimensional roughness elements of equivalent size and shape. For the present flow conditions a row of triangular excrescences was found to be successful in tripping the boundary layer for all cases tested, although the lowest value of Re_k used was 3200. An isolated, rounded excrescence was found to be an effective trip for $Re_k = 2100$, whereas for a value of 1100 the trip was not effective but promoted earlier transition behind the excrescence.

IV. Conclusions

Data from the intermittent transitional region of hypervelocity boundary layers with smooth, isolated, and distributed roughness elements have been obtained using an array of thin-film heat-transfer gauges. The flow in this region is qualitatively and, in some aspects, quantitatively similar to that observed in lower enthalpy flows.

In hypervelocity shock-tunnel flows, for a surface free from large excrescences, the results of Rasheed et al.[5] show that it is possible to delay the onset of transition by attenuating second-mode acoustic disturbances. In the absence of such control, it can therefore be assumed that transition initiation occurs through breakdown of second-mode disturbances. The present results then show that the developments in the intermittent transitional region for the present flows are similar to those observed in boundary layers for which the intermittent region starts with the breakdown of Tollmien–Schlichting waves.

The present results show that turbulent spots grow at a more slender angle than at lower Mach numbers, in line with the data of Ref. 19. There is evidence in the transition lengths that turbulent spot initiation rates are high in the present flows.

Surface roughness in the form of a row of triangular teeth with $h/\delta \approx 1$ was found to promote earlier transition at the low and high enthalpy conditions. For all cases $Re_k > 3200$. An isolated rounded roughness element with a height 50% of the boundary-layer thickness ($Re_k = 2100$) was found to be capable of producing a turbulent patch immediately behind the element. At a lower Reynolds number, when the excrescence height was approximately 44% of the boundary layer thickness and Re_k was 1100, the element did not immediately promote transition, but results indicate that transition at this condition started earlier directly behind the disturbance.

Acknowledgment

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M. Sichel
Associate Editor